

Characterization of Magnetically Accelerated Flyer Plates

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The intense magnetic field generated by the 20 megaampere Z machine at Sandia National Laboratories is being used as a pressure source for material science studies. An application we have studied in great detail involves using the intense magnetic field to accelerate flyer plates (small metal disks) to very high velocities (> 20 km/s) for use in shock loading experiments. We have used highly accurate velocity interferometry measurements (error $< 1\%$) in conjunction with one dimensional magnetohydrodynamic (MHD) simulation to elucidate details of the flyer dynamics. One dimensional MHD simulations are able to produce experimental results with a high degree of accuracy, thereby revealing otherwise unobtainable, but physically meaningful information about magnetically accelerated flyers on Z. Comparisons of simulation results with time resolved measurements of velocity from a shock loading experiment involving a 925 micron aluminum flyer are presented. Results show that Joule heating related to magnetic diffusion determines the minimum possible initial thickness of a flyer.

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The intense magnetic field generated by the Z machine [1] at Sandia National Laboratories is being used as a pressure source for material science studies [2-5]. The machine can deliver up to 20 megaamperes (MA) of current to a short-circuited load in 200 nanoseconds (ns), which generates a peak magnetic field in the megagauss range. An application we have studied in great detail involves using the intense magnetic field to accelerate flyer plates (small metal disks) to very high velocities [6] for use in shock loading experiments. The flyer plate is allowed to collide with a target, which generates a shock in the target material. Measurements of the flyer velocity and the shock speed in the material are used in conjunction with the Rankine-Hugoniot jump conditions [7] to obtain the density, pressure, and internal energy of the material. In this way, a 1.0 cm diameter, 0.085 cm thick aluminum (Al) flyer plate was accelerated to 21 km/s to obtain state-of-the-art equation of state (EOS) data of deuterium for pressures up to 700 kilobars (kbar) [5].

The magnitude of the shock generated in the target, in addition to the measurement error, is dependent on the condition of the flyer plate at impact, which in turn depends on the time history of the pressure drive. Indeed, the validity of the technique depends on the generation of a steady shock in the material sample, which places requirements on the condition of the flyer at impact. Thus, it is important to know the state of the flyer when it impacts the target. This information, in addition to the drive pressure history, is contained implicitly in the ensemble of measurements taken in a shock loading experiment [3, 5].

In this Letter, we present results from 1-dimensional (1D) magnetohydrodynamic (MHD) simulations of shock loading experiments that produce the measured velocities with a high degree of accuracy. The excellent agreement between the measured and simulated velocities suggests that the flyer dynamics predicted by the calculations are physically realistic. As will be shown, detailed comparisons of MHD simulations with experiment reveal a great deal about the physics of magnetically accelerating flyer plates to ultra-high velocities.

A 2D cross section of a typical flyer configuration (shock physics load) used on Z is shown schematically in Fig. 1 [5]. The actual geometry is 3D, with a similar cross section in the plane perpendicular to the figure. The magnetic pressure ($P = B^2/2\mu_0$) compresses the anode (A) and cathode (K) material, which causes the air-gap [void (V) between anode and cathode] to increase. The flyer (F) moves independently of the surrounding anode without losing electrical contact after the initial pressure wave releases from the front [target (T)] side of the flyer, and returns to the back (magnetic drive) side. The magnetic force ($\mathbf{J} \times \mathbf{B}$) accelerates the flyer to peak velocity in approximately 0.3 cm, after which time it impacts the target. Measurements indicate that the flyer bows in the plane of Fig. 1 (with ends farther from target than center), but that the central 40% remains highly planar. This provides the impetus for using 1D simulation to model the problem. The region simulated (R) is bounded by the dashed line in Fig. 1.

The configuration used for 1D simulations is shown schematically in Fig. 2. As in the experiment, the target

(T) is comprised of a 0.1 cm thick Al impact plate abutted against a lithium fluoride (LiF) window. The Al flyer (F) is 0.0925 cm thick.

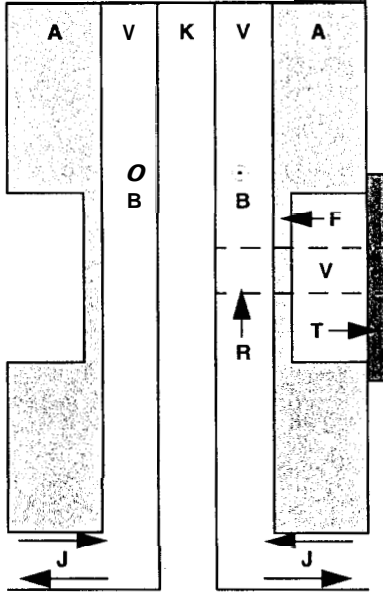


FIG. 1. Cross section of 3D flyer configuration used in shock loading experiments. Anode (A) and cathode (K) are attached in a short circuit at the top of the figure. The flyer (F) is formed by boring out anode material to obtain a desired thickness. The flyer is accelerated across void (V) and impacts a target (T). The directions of the surface current density (J) and magnetic field (B) are indicated by arrows. A dashed line bounds the 1D simulation region (R).

One-dimensional Eulerian simulations were performed using the finite element, arbitrary Lagrangian-Eulerian, MHD code ALEGRA [8]. MHD equations for a compressible material with strength were solved (e.g., see [9, 10]). A wide range EOS was used for Al [11], in addition to models for the thermal and electrical conductivities [12, 13]. ALEGRA includes artificial viscosity, which broadens shock fronts. To ensure resolution of shocks, 50 zones are used across the flyer and 54 across the Al impact plate, with similar resolution in the LiF. One zone is used in the y-direction.

The cathode is included only as a fixed conducting boundary from which to input the magnetic field, which is given by $B = \mu_0 I(t)/S$. Due to the 1D nature of the simulation, the drive current [$I(t)$] and the magnetic field scale factor S are free parameters. Nevertheless, a measured waveform was used for $I(t)$, and the value of $S = 4.5$ cm was calculated using static, 3D electromagnetic simulation. The drive current measurement is much less accurate than the velocity measurements

(10% vs. 1%), so slight adjustments were made to the current waveform to produce good agreement with the experiment, which determines the actual drive pressure history. In effect, this is equivalent to using the measured flyer velocity to perform a backward integration of the MHD equations to obtain the drive pressure history. The $I(t)$ used in the simulations and corresponding magnetic pressure are shown in Fig. 3.

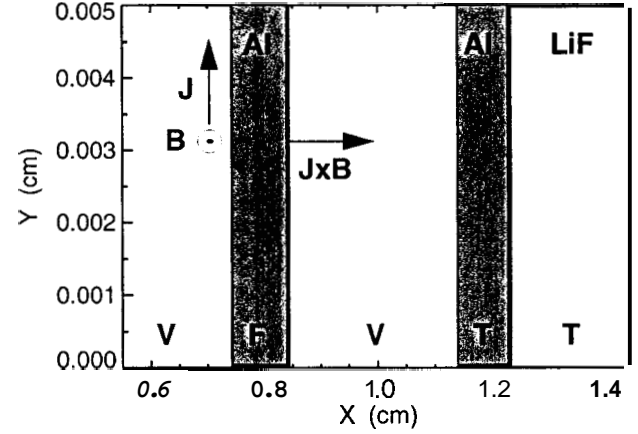


FIG. 2. Schematic of 1D simulation configuration (region R in Fig. 1). The flyer (F) material is Al. The target (T) is comprised of an Al impact plate abutted against a LiF window. The flyer is the anode. The left-hand boundary of the figure is the cathode, which is used to input the drive current.

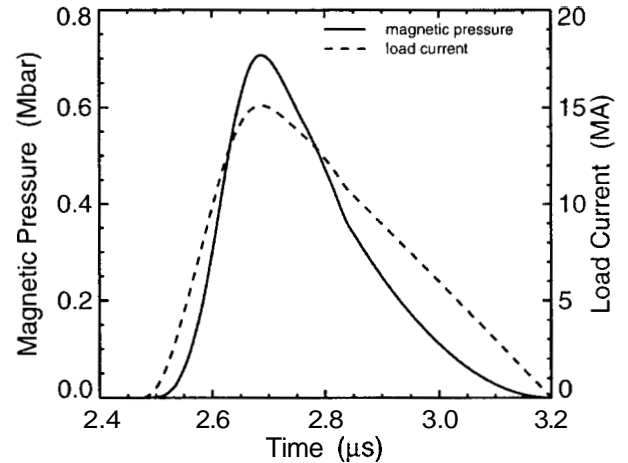


FIG. 3. Current and pressure histories that produce measured flyer plate velocities using 1D MHD simulation.

In the experiment, VISAR measurements are used to determine the flyer (front) surface velocity and the velocity of the Al/LiF interface [3-5]. A comparison of these measurements with the simulated results is

shown in Figs. 4a and 4b. Considering that the measurement error is on the order of 1%, the agreement between simulation and experiment is excellent. This provides evidence for the validity of the physics models used in ALEGRA, and implies that the ensemble of simulation results is realistic.

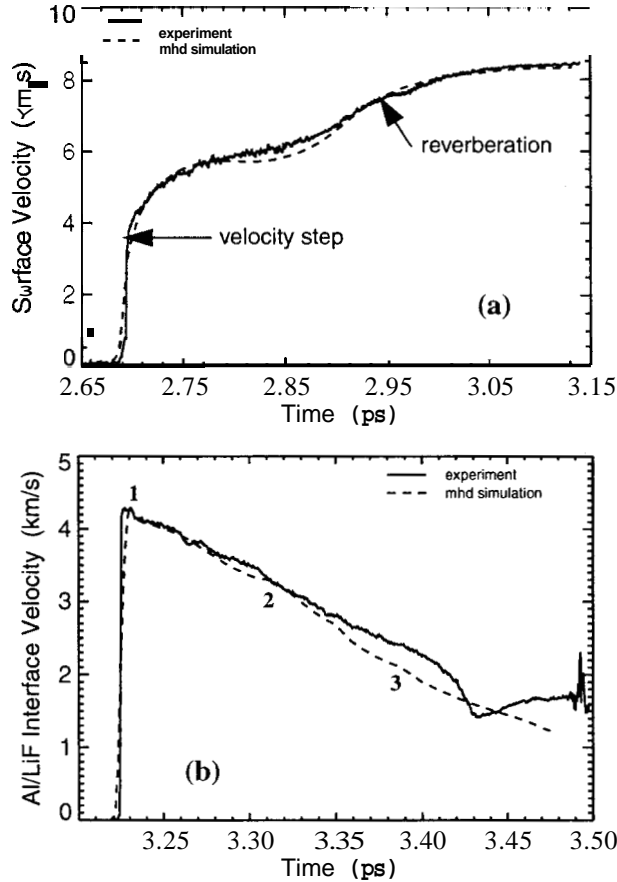


FIG. 4. (a) Comparison of simulated and measured flyer velocity. The initial step in velocity is due to shock formation in the flyer, and is proportional to the peak current. Multiple transits of the pressure wave through the flyer creates a distinct reverberation. (b), Comparison of simulated and measured Al/LiF interface velocity, which is induced through the collision of the flyer with the target. The numbers 1, 2, and 3 respectively designate solid-liquid, liquid-boiling, and boiling-vapor phase transitions in the flyer material, which were determined from simulation (see Fig. 5).

Initial comparisons of simulation results with measurements did not agree well, the cause of which was determined to be a rapid drop in electrical conductivity when melting occurred. The level of agreement exhibited in Fig. 4 was produced only after the electrical conductivity model of Al was improved using recent ab

initio quantum molecular dynamics calculations [13].

Simulations show that the flyer velocity (Fig. 4a) is comprised of an initial step due to the shock induced by the magnetic pressure, a distinct reverberation due to a double transit of the pressure wave across the flyer, and a thermal component due to Joule heating induced ablation of flyer material. This latter component accounts for about 15% of the final velocity. Although reverberations occur in general, a well-defined event is observed (as in Fig. 4a) when the rise time to peak current is greater than the round trip transit time of the initial pressure wave induced in the flyer. The velocity step is proportional to the square root of the shock pressure (as can be shown for strong shocks [14]) and therefore, is proportional to the peak current. In the absence of ablation and inductive effects, the final flyer velocity is proportional to the peak current squared.

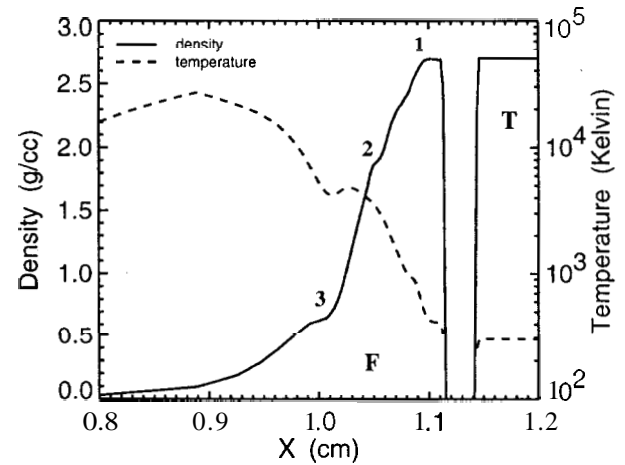


FIG. 5. Snapshot of the simulated density and temperature in the Al flyer (F) just before it impacts the target (T). Values of these quantities indicate that the flyer material is comprised of layers that are in different phases. On the target side, approximately 0.014 cm of the flyer material is in the solid state (density=2.7 g/cc), succeeded by liquid and boiling layers, and terminating in a hot vapor tail. The solid-liquid, liquid-boiling, and boiling-vapor phase transitions are indicated using the numbers 1, 2, and 3, respectively [see Fig. 4b].

In a symmetric collision (flyer and target materials identical) a material velocity equal to one-half the flyer velocity is induced in the target (slightly less if the flyer is shock heated). The Al/LiF interface (Fig. 4b) will move with this velocity (because the shock impedance of LiF is close to that of Al) until the release wave from the flyer back surface catches up to it. This behavior is evident in Fig. 4b (between the initial rise in velocity and the point marked 1), and indicates that some fraction of flyer remains at solid density (2.7 g/cc) at

impact.

Figure 5 is a snapshot of the simulated density and temperature in the flyer just before it impacts the AI part of the target [3.1 microseconds (μs)]. The figure shows that approximately 0.014 cm (15%) of flyer material remains at solid density, which is consistent with the conclusion drawn from the measurement.

The initial shock transmitted through the flyer causes a slight heating of the flyer material (~ 100 Kelvin). However, the diffusion of the magnetic field into the flyer substantially heats the material (up to 30,000 Kelvin), thereby resulting in a layered flyer comprised of solid, liquid, boiling, and vaporized regions. These phase transitions are marked by the numbers 1 (solid-liquid), 2 (liquid-boiling), and 3 (boiling-vapor) in Fig. 5. The solid-liquid transition marks the point to which significant magnetic field has diffused into the flyer.

The interface velocity time history is quite sensitive to derivatives in the flyer density. The phase transitions in the flyer material are echoed in the interface velocity, which is indicated in Fig. 4b using the numbers 1, 2, and 3. The solid-liquid transition (1) is clear in the measurement. A feature indicative of the liquid-boiling transition (2) is also evident at the same location as in the simulation. However, the simulated and measured interface velocities diverge near the boiling-vapor transition (3). This part of the simulation is more sensitive to different AI EOSs than are transitions 1 and 2, and may indicate the need for more research in this region of phase space. The large kink in the measurement cannot be produced in 1D simulations, and is likely due to release waves that originate at the lateral edges of the flyer and propagate toward the center.

One-dimensional simulations in which the peak current was varied up to a maximum value of 25.5 MA show that the hydrodynamic pressure wave induced in the flyer is faster than the magnetic diffusion rate (R_B) in general. This guarantees that Joule heating does not destroy the flyer before it starts to move. In the range of peak drive current $15 \leq I \leq 25.5$ MA, R_B varies linearly with I as $R_B = 0.10I_{\text{max}} + 0.22$ (mm/ μs), where I is in MA. To ensure that the flyer arrives at the target with some material unaffected by the magnetic field the initial flyer thickness (D) must be greater than $D_{\text{min}} = R_B t_a$, where t_a is the time it takes to accelerate the flyer to the target. Alternatively, magnetic diffusion places a requirement on t_a for a given D .

In general, D must be several hundred microns thicker than D_{min} (depending on velocity) to obtain a near-solid density impactor. However, D cannot be increased arbitrarily because shock formation at large drive pressures (\sim megabars) can also destroy the flyer. Thus, magnetically accelerating flyers to ultra-high velocities (>20 km/s) for shock loading experiments

imposes limits on the flyer thickness, which must be large enough to offset magnetic diffusion yet thin enough to prevent shock formation.

We have used 1D MHD simulation in conjunction with highly accurate experimental data to elucidate the dynamics of magnetically accelerated flyers on the Z machine. The demonstrated ability of ALEGRA to accurately produce measured velocities has allowed us to extract otherwise unobtainable, but physically meaningful information from the simulations, which has led to a deeper understanding of the physics and has proved valuable in the interpretation and design of EOS experiments on Z in general.

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